An integrated workflow for stress and flow modelling using outcrop-derived discrete fracture networks

Fluid flow in naturally fractured reservoirs is often controlled by sub-seismic-scale fracture networks. Although the fracture network can be partly sampled in the direct vicinity of wells, the inter-well scale network is poorly constrained in fractured reservoir models. Outcrop analogues can provide data for populating domains of the reservoir model where no direct measurements are available. However, extracting relevant statistics from large outcrops representative of inter-well scale fracture networks remains challenging. Recent advances in outcrop imaging provide high-resolution datasets that can cover areas of several hundred to several hundred meters, i.e., the domain between adjacent wells, but even then, data from the high-resolution models is often upscaled to reservoir flow grids, resulting in loss of accuracy. We present a workflow that uses photorealistic georeferenced outcrop models to construct geomechanical and fluid flow models containing thousands of discrete fractures covering sufficiently large areas, that does not require upscaling to model permeability. This workflow seamlessly integrates geomechanical Finite Element models with flow models that take into account stress-sensitive fracture permeability and matrix flow to determine the full permeability tensor. The applicability of this workflow is illustrated using an outcropping carbonate pavement in the Potiguar basin in Brazil, from which 1082 fractures are digitised. The permeability tensor for a range of matrix permeabilities shows that conventional upscaling to effective grid properties leads to potential underestimation of the true permeability and the orientation of principal permeabilities. The presented workflow yields the full permeability tensor model of discrete fracture networks with stress-induced apertures, instead of relying on effective properties as most conventional flow models do.
On the connectivity anisotropy in fluvial Hot Sedimentary Aquifers and its influence on geothermal doublet performance

This study finds that the geothermal doublet layout with respect to the paleo flow direction in fluvial sedimentary reservoirs could significantly affect pump energy losses. These losses can be reduced by up to 10% if a doublet well pair is oriented parallel to the paleo flow trend compared to perpendicular. The chance that flow paths are formed perpendicular to this trend strongly depends on the net sandstone volume in the reservoir. Detailed fluvial facies architecture realisations which are used in this study, are generated with a process-based approach utilizing geological data from the Lower Cretaceous Nieuwerkerk Formation in the West Netherlands Basin. Finally, this study emphasizes the importance of detailed facies architecture modelling for the assessment of both risks and production strategies in Hot Sedimentary Aquifers.

General information
State: Published
Organisations: Centre for oil and gas – DTU, Delft University of Technology, University of Leuven
Authors: Willems, C. J. (Ekstern), Nick, H. (Intern), Donselaar, M. E. (Ekstern), Weltje, G. J. (Ekstern), Bruhn, D. F. (Ekstern)
Number of pages: 12
Pages: 222-233
Publication date: 2017
Main Research Area: Technical/natural sciences

Publication information
Journal: Geothermics
Volume: 65
ISSN (Print): 0375-6505
A geometrically based method for predicting stress-induced fracture aperture and flow in discrete fracture networks

Modeling of fluid flow in naturally fractured reservoirs is often done through modeling and upscaling of discrete fracture networks (DFNs). The two-dimensional fracture geometry required for DFNs is obtained from subsurface and outcropping analog data. However, these data provide little information on subsurface fracture aperture, which is essential for quantifying porosity and permeability. Apertures are difficult to obtain from either outcropping or subsurface data and are therefore often based on fracture size or scaling relationships, but these do not consider the orientation and spatial distribution of fractures with respect to the in situ stress field. Using finite-element simulations, mechanical aperture can be modeled explicitly, but because changes in fracture geometry require renewed meshing and simulating, this approach is not easily integrated into subsurface DFN modeling workflows. We present a geometrically based method for calculating the shear-induced hydraulic aperture, that is, an aperture of up to 0.5 mm (0.02 in.) that can result from shear
displacement along irregular fracture walls. The geometrically based method does not require numerical simulations, but it can instead be directly applied to DFNs using the fracture orientation and spacing distributions in combination with an estimate of the regional stress tensor and orientation. The frequency distribution of hydraulic aperture from the geometrically based method is compared with finite-element models constructed from five real fracture networks, digitized from outcropping pavements. These networks cover a wide range of possible geometries and spatial distributions. The geometrically based method predicts the average hydraulic aperture and equivalent permeability of fractured porous media with error margins of less than 5%.

General information
State: Published
Organisations: Centre for oil and gas – DTU, Delft University of Technology
Authors: Bisdom, K. (Ekstern), Bertotti, G. (Ekstern), Nick, H. (Intern)
Publication date: 2016
Main Research Area: Technical/natural sciences

Publication information
Journal: Geological Society of America Bulletin
Volume: 100
Issue number: 7
ISSN (Print): 0016-7606
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 2.426 SNIP 1.601 CiteScore 3.86
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 2.273 SNIP 1.486 CiteScore 3.41
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 2.557 SNIP 1.743 CiteScore 3.87
Web of Science (2014): Indexed yes
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 2.843 SNIP 2.119 CiteScore 4.77
ISI indexed (2013): ISI indexed yes
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 2.95 SNIP 1.876 CiteScore 4.06
ISI indexed (2012): ISI indexed yes
Web of Science (2012): Indexed yes
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 2.794 SNIP 1.724 CiteScore 3.33
ISI indexed (2011): ISI indexed yes
BFI (2010): BFI-level 1
Scopus rating (2010): SJR 2.823 SNIP 1.91
BFI (2009): BFI-level 2
Scopus rating (2009): SJR 2.716 SNIP 1.799
Web of Science (2009): Indexed yes
BFI (2008): BFI-level 2
Scopus rating (2008): SJR 2.884 SNIP 1.902
Web of Science (2008): Indexed yes
Scopus rating (2007): SJR 2.76 SNIP 1.945
Scopus rating (2006): SJR 2.421 SNIP 2.032
Scopus rating (2005): SJR 2.354 SNIP 1.871
Scopus rating (2004): SJR 2.457 SNIP 1.695
Scopus rating (2003): SJR 2.336 SNIP 1.682
Scopus rating (2002): SJR 2.158 SNIP 1.691
Scopus rating (2001): SJR 2.409 SNIP 1.641
Scopus rating (2000): SJR 2.209 SNIP 1.707
Application of infrared thermography for temperature distributions in fluid-saturated porous media

Infrared thermography has increasingly gained importance because of environmental and technological advancements of this method and is applied in a variety of disciplines related to non-isothermal flow. However, it has not been used so far for quantitative thermal analysis in saturated porous media. This article suggests infrared thermographic approach to obtain the entire surface temperature distribution(s) in water-saturated porous media. For this purpose, infrared thermal analysis is applied with in situ calibration for a better understanding of the heat transfer processes in porous media. Calibration is achieved with a combination of invasive sensors which are inserted into the medium and non-invasive thermal sensors in which sensors are not inserted to measure temperatures but it works through the detection of infrared radiation emitted from the surface. Thermocouples of relatively thin diameter are used to minimize the disturbance for flow. Thermocouples give the temperature values at specified positions inside the porous medium, and these values are compared with the values suggested by the infrared thermographic device at the same positions, in the calibration exercise. The calibration process was repeated for different temperatures and flow rates to get the temperature distributions of the whole material inside the system. This technique enables us to measure accurate two-dimensional temperature distributions, which is not possible by using thermocouples only. Continuous point heat sources at different flow rates and temperatures are studied experimentally. Additionally, it offers numerical simulations of the experiments utilizing a finite element-based model. A two-dimensional density and viscosity-dependent flow and transport model accounting for thermal dispersion is utilized to simulate the experimental results. Possible small heat losses from the surface are incorporated in the model according to the properties and thickness of the Plexiglass material used for the construction of the experiment tank. The numerical results agree well with the experimental observations.

General information
State: Published
Organisations: Centre for oil and gas – DTU, Utrecht University
Authors: Imran, M. (Ekstern), Nick, H. (Intern), Schotting, R. J. (Ekstern)
Number of pages: 16
Publication date: 2016
Main Research Area: Technical/natural sciences

Publication information
Journal: Arabian Journal of Geosciences
Volume: 9
Issue number: 4
ISSN (Print): 1866-7511
Ratings:
BFI (2017): BFI-level 1
Web of Science (2017): Indexed Yes
BFI (2016): BFI-level 1
Scopus rating (2016): SJR 0.371 SNIP 0.723 CiteScore 1
Web of Science (2016): Indexed yes
BFI (2015): BFI-level 1
Scopus rating (2015): SJR 0.413 SNIP 0.984 CiteScore 0.85
BFI (2014): BFI-level 1
Scopus rating (2014): SJR 0.346 SNIP 0.731 CiteScore 0.77
BFI (2013): BFI-level 1
Scopus rating (2013): SJR 0.312 SNIP 1.136 CiteScore 1.21
BFI (2012): BFI-level 1
Scopus rating (2012): SJR 0.262 SNIP 0.657 CiteScore 0.75
BFI (2011): BFI-level 1
Scopus rating (2011): SJR 0.2 SNIP 0.349 CiteScore 0.62
Scopus rating (2010): SJR 0.136 SNIP 0.179
Scopus rating (2009): SJR 0.11 SNIP 0.062
Original language: English
Infrared thermography, Saturated porous medium, Temperature measurement, Thermal dispersion
DOIs:
10.1007/s12517-016-2353-6
Source: Findit
Source-ID: 2303496948
The impact of different aperture distribution models and critical stress criteria on equivalent permeability in fractured rocks

Predicting equivalent permeability in fractured reservoirs requires an understanding of the fracture network geometry and apertures. There are different methods for defining aperture, based on outcrop observations (power law scaling), fundamental mechanics (sublinear length-aperture scaling), and experiments (Barton-Bandis conductive shearing). Each method predicts heterogeneous apertures, even along single fractures (i.e., intrafracture variations), but most fractured reservoir models imply constant apertures for single fractures. We compare the relative differences in aperture and permeability predicted by three aperture methods, where permeability is modeled in explicit fracture networks with coupled fracture-matrix flow. Aperture varies along single fractures, and geomechanical relations are used to identify which fractures are critically stressed. The aperture models are applied to real-world large-scale fracture networks. (Sub)linear length scaling predicts the largest average aperture and equivalent permeability. Barton-Bandis aperture is smaller, predicting on average a sixfold increase compared to matrix permeability. Application of critical stress criteria results in a decrease in the fraction of open fractures. For the applied stress conditions, Coulomb predicts that 50% of the network is critically stressed, compared to 80% for Barton-Bandis peak shear. The impact of the fracture network on equivalent permeability depends on the matrix hydraulic properties, as in a low-permeable matrix, intrafracture connectivity, i.e., the opening along a single fracture, controls equivalent permeability, whereas for a more permeable matrix, absolute apertures have a larger impact. Quantification of fracture flow regimes using only the ratio of fracture versus matrix permeability is insufficient, as these regimes also depend on aperture variations within fractures.
Aperture has a controlling impact on porosity and permeability and is a source of uncertainty in modeling of naturally fractured reservoirs. This uncertainty results from difficulties in accurately quantifying aperture in the subsurface and from a limited fundamental understanding of the mechanical and diagenetic processes that control aperture. In the absence of cement bridges and high pore pressure, fractures in the subsurface are generally considered to be closed. However, experimental work, outcrop analyses and subsurface data show that some fractures remain open, and that aperture varies even along a single fracture. However, most fracture flow models consider constant apertures for fractures. We create a stress-dependent heterogeneous aperture by combining Finite Element modeling of discrete fracture networks with an empirical aperture model. Using a modeling approach that considers fractures explicitly, we quantify equivalent permeability, i.e. combined matrix and stress-dependent fracture flow. Fracture networks extracted from a large outcropping pavement form the basis of these models. The results show that the angle between fracture strike and $\sigma_1$ has a controlling impact on aperture and permeability, where hydraulic opening is maximum for an angle of 15°. At this angle, the fracture experiences a minor amount of shear displacement that allows the fracture to remain open even when fluid pressure is lower than the local normal stress. Averaging the heterogeneous aperture to scale up permeability probably results in an underestimation of flow, indicating the need to incorporate full aperture distributions rather than simplified aperture models in reservoir-scale flow models.
The influence of facies heterogeneity on the doublet performance in low-enthalpy geothermal sedimentary reservoirs

A three-dimensional model is used to study the influence of facies heterogeneity on energy production under different operational conditions of low-enthalpy geothermal doublet systems. Process-based facies modelling is utilised for the Nieuwerkerk sedimentary formation in the West Netherlands Basin to construct realistic reservoir models honouring geological heterogeneity. A finite element based reservoir simulator is used to model the fluid flow and heat transfer over time. A series of simulations is carried out to examine the effects of reservoir heterogeneity (Net-to-Gross ratio, N/G) on the life time and the energy recovery rate for different discharge rates and the production temperature (Tmin) above which
the doublet is working. With respect to the results, we propose a design model to estimate the life time and energy recovery rate of the geothermal doublet. The life time is estimated as a function of N/G, Tmin and discharge rate, while the design model for the energy recovery rate is only a function of N/G and Tmin. Both life time and recovery show a positive relation with an increasing N/G. Further our results suggest that neglecting details of process-based facies modelling may lead to significant errors in predicting the life time of low-enthalpy geothermal systems for N/G values below 70%.

**General information**
- State: Published
- Organisations: Centre for oil and gas – DTU, Delft University of Technology
- Authors: Crooijmans, R. A. (Ekstern), Willems, C. J. L. (Ekstern), Nick, H. (Intern), Bruhn, D. F. (Ekstern)
- Number of pages: 11
- Pages: 209-219
- Publication date: 2016
- Main Research Area: Technical/natural sciences

**Publication information**
- Journal: Geothermics
- Volume: 64
- ISSN (Print): 0375-6505
- Ratings:
  - BFI (2017): BFI-level 1
  - Web of Science (2017): Indexed Yes
  - BFI (2016): BFI-level 1
  - Scopus rating (2016): SJR 0.943 SNIP 1.417 CiteScore 2.67
  - Web of Science (2016): Indexed yes
  - BFI (2015): BFI-level 1
  - Scopus rating (2015): SJR 1.344 SNIP 1.987 CiteScore 2.99
  - Web of Science (2015): Indexed yes
  - BFI (2014): BFI-level 1
  - Scopus rating (2014): SJR 1.924 SNIP 3.002 CiteScore 3.61
  - Web of Science (2014): Indexed yes
  - BFI (2013): BFI-level 1
  - Scopus rating (2013): SJR 1.851 SNIP 2.423 CiteScore 3.08
  - ISI indexed (2013): ISI indexed yes
  - BFI (2012): BFI-level 1
  - Scopus rating (2012): SJR 1.177 SNIP 1.81 CiteScore 1.89
  - ISI indexed (2012): ISI indexed yes
  - BFI (2011): BFI-level 1
  - Scopus rating (2011): SJR 0.955 SNIP 1.973 CiteScore 1.9
  - ISI indexed (2011): ISI indexed yes
  - BFI (2010): BFI-level 1
  - Scopus rating (2010): SJR 0.795 SNIP 1.757
  - BFI (2009): BFI-level 1
  - Scopus rating (2009): SJR 1.009 SNIP 2.693
  - BFI (2008): BFI-level 1
  - Scopus rating (2008): SJR 0.839 SNIP 1.377
  - Scopus rating (2007): SJR 0.736 SNIP 1.428
  - Scopus rating (2006): SJR 0.472 SNIP 1.301
  - Web of Science (2006): Indexed yes
  - Scopus rating (2005): SJR 0.674 SNIP 0.852
  - Web of Science (2005): Indexed yes
  - Scopus rating (2004): SJR 0.284 SNIP 0.806
  - Scopus rating (2003): SJR 0.546 SNIP 1.078
  - Scopus rating (2002): SJR 0.592 SNIP 0.721
  - Scopus rating (2001): SJR 0.345 SNIP 0.731
  - Scopus rating (2000): SJR 0.311 SNIP 0.809
  - Scopus rating (1999): SJR 0.416 SNIP 0.773
Projects:

**Numerical modelling of near wellbore flow**
Department of Applied Mathematics and Computer Science  
Period: 01/07/2017 → 30/06/2020  
Number of participants: 3  
Phd Student: 
Kadeethum, Teeratorn (Intern)  
Supervisor: 
Salimzadeh, Saeed (Intern)  
Main Supervisor: 
Nick, Hamid (Intern)  

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: Institut stipendie (DTU)  
Project: PhD

**Numerical simulation of modified brine water flooding in chalk reservoirs**
Department of Applied Mathematics and Computer Science  
Period: 01/02/2017 → 31/01/2020  
Number of participants: 3  
Phd Student: 
Baghooee, Hadise (Intern)  
Supervisor: 
Eftekhari, Ali Akbar (Intern)  
Main Supervisor: 
Nick, Hamid (Intern)  

**Financing sources**  
Source: Internal funding (public)  
Name of research programme: Institut stipendie (DTU)  
Project: PhD

**Production performance of radial water-jet drilled wells: a modelling and laboratory study**
Department of Applied Mathematics and Computer Science  
Period: 01/10/2016 → 30/09/2019  
Number of participants: 4  
Phd Student: 
Medetbekova, Maiya (Intern)  
Supervisor: 
Christensen, Helle Torp (Intern)  
Salimzadeh, Saeed (Intern)  
Main Supervisor: 
Nick, Hamid (Intern)  

**Financing sources**
Simulation and Optimization of Oil Reservoirs in the Danish North Sea

Department of Applied Mathematics and Computer Science
Period: 01/12/2015 → 30/11/2018
Number of participants: 4
PhD Student:
Hørsholt, Steen (Intern)
Supervisor:
Capolei, Andrea (Intern)
Nick, Hamid (Intern)
Main Supervisor:
Jørgensen, John Bagterp (Intern)

Financing sources
Source: Internal funding (public)
Name of research programme: Eksternt finansieret virksomhed
Project: PhD